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PATENT APPLICATION

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of:)
YASUO SUDA) Examiner: G. Solomon
Application No.: 09/604,743) Group Art Unit: 2615
Filed: June 28, 2000)
For: IMAGE PICKUP APPARATUS) October 26, 2004

MAIL STOP AF
Commissioner For Patents
P.O. Box 1450
Alexandria, VA 22313-1450

LETTER FORWARDING SUBSTITUTE SPECIFICATION

Sir:

Applicant submits herewith a substitute specification to replace the specification originally filed in the present application. A marked-up copy of the original specification, showing the matter added and deleted in the substitute specification, is also submitted herewith. Applicant submits that the substitute specification contains no new matter.

Applicant believes that no fees should be incurred in connection with filing this paper. However, the Commissioner is authorized to charge Deposit Account No. 06-1205, should any fees be required.

Favorable consideration is requested.

Applicant's undersigned attorney may be reached in our Washington, D.C., office by telephone at (202) 530-1010. All correspondence should continue to be directed to our address below.

Respectfully submitted,

Anne M. Maher

Attorney for Applicant
Anne M. Maher
Registration No. 38,231

FITZPATRICK, CELLA, HARPER & SCINTO
30 Rockefeller Plaza
New York, New York 10112-3801
Facsimile: (212) 218-2200

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CFO 14594 US

(Substitute Specification for Application No. 09/604,743)

IMAGE PICKUP APPARATUS

BACKGROUND OF THE INVENTION

5 Field of the Invention

The present invention relates to an image pickup apparatus capable of picking up a dynamic image or a still image such as a video camera.

Related Background Art

In a digital color camera, in response to depressing a RELEASE button, an object image is exposed to a solid-state image pickup element such as a CCD or a CMOS sensor for a desired time period, an image signal thus obtained is converted into a digital signal, and then is subject to predetermined processing such as YC processing, and an image signal of a predetermined format is obtained. This digital image signal is recorded in a semiconductor memory. The recorded image signal can be read according to the need to be reproduced as a signal capable of being displayed or printed, and can be output to a monitor or the like to visualize the recorded image.

Three methods are known for exposing an object image. One is a method in which RGB color filters are formed on a solid-state image pickup element, for example, on a 2 x 2 pixel basis to give wavelength selectability to each of the pixels,

thus separating the object image into RGB images. Another is a method used when a solid-state image pickup element does not have wavelength selectability, in which optical filters having wavelength selectability are inserted in an image pickup optical system, and time-sequential switching of the optical filter is carried out. The third is
5 a method in which a color separation optical system is added at the back of the image pickup optical system to take in images using different image pickup elements with regard to respective wavelength ranges.

A conventional digital color camera often adopts the first method described above. Japanese Patent Application Laid-open No. 9-172649 discloses the third
10 method described above, while Japanese Patent Application Laid-open Nos. 7-84177 and 7-123418 disclose the second method described above.

However, in all three methods described above, since the image pickup optical system is shared by all wavelength ranges, it is necessary to have satisfactory optical performance over the whole visible range. Generally, since an image pickup
15 optical system uses light refraction in optical glass or in optical transparent resin as its imaging principle, the index of refraction changes according to the wavelength, and, in order to prevent the image quality from being degraded due to such change, an optical design method referred to as achromatism is used. As a result, it is difficult to form a high performance image pickup optical system using a simple
20 lens. This is an obstacle to miniaturization of the image pickup optical system.

SUMMARY OF THE INVENTION

According to one aspect of the present invention, there is provided an

image pickup apparatus comprising first and second image pickup portions for receiving at least a first wavelength component of object light and a second wavelength component of the object light different from the first wavelength component, respectively, and first and second optical systems for guiding the first and second wavelength components of the object light to be received by the first and second image pickup portions to the first and second image pickup portions, respectively, via different optical paths, the first and second optical systems being constructed such that the focal length of the first optical system with regard to the first wavelength component is equal to the focal length of the second optical system with regard to the second wavelength component. The present invention can result in an image pickup apparatus which is small-sized and has high image quality.

Other aspects of the present invention will become apparent from the following preferred embodiment.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a sectional view of an image pickup system of a digital color camera according to an embodiment of the present invention;

Fig. 2 is a front view of a solid-state image pickup element of the image pickup system shown in Fig. 1;

Fig. 3 is a front view of a diaphragm of the image pickup system shown in Fig. 1;

Fig. 4 illustrates the ranges where optical filters of the image pickup system shown in Fig. 1 are formed;

Fig. 5 illustrates an objective lens of the image pickup system shown in Fig. 1 which is viewed from the side where light is projected;

Fig. 6 is a graph showing the spectral transmission factor characteristics of the optical filters of the image pickup system shown in Fig. 1;

5 Fig. 7 is a graph showing the spectral transmission factor characteristics of a color purity correction filter of the image pickup system shown in Fig. 1;

Fig. 8 is a graph showing the spectral transmission factor characteristics of a photochromic glass of the image pickup system shown in Fig. 1;

10 Fig. 9 is a graph showing the transmission factor distribution of a transmission factor distribution type filter of the image pickup system shown in Fig. 1;

Fig. 10 is a graph showing the OTF characteristics of the objective lens of the image pickup system shown in Fig. 1;

15 Fig. 11 is a graph showing the intensity distribution in an image by the image pickup system shown in Fig. 1;

Fig. 12 is an explanatory view for explaining the setting of the intervals between lens portions of the image pickup system shown in Fig. 1;

Fig. 13 is an explanatory view for explaining the positions of images of an object at infinity of the image pickup system shown in Fig. 1;

20 Fig. 14 is a block diagram of a signal processing system of the digital color camera shown in Fig. 1;

Fig. 15 illustrates the positional relationship of the image pickup region for R and B pixels with respect to the image pickup region for a G pixel of the image

pickup system shown in Fig. 1;

Fig. 16 is an explanatory view of interpolation processing of the digital color camera shown in Fig. 1; and

Figs. 17A, 17B, and 17C illustrate the overall structure of the digital color camera shown in Fig. 1.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Preferred embodiments of the present invention are now described in detail with reference to the drawings.

Figs. 17A, 17B, and 17C illustrate the overall structure of a digital color camera according to a first embodiment of the present invention. Figs. 17A, 17C, and 17B are a front view, a rear view, and a sectional view taken along the line 17B-17B in the rear view of Fig. 17C, respectively.

In Figs. 17A, 17B, and 17C, reference numeral 1 denotes a camera body. An illuminating light intake window 2 formed of a white diffusing plate is positioned at the back of a color liquid crystal monitor 4. Reference numerals 5 and 6 denote a main switch and a RELEASE button, respectively. Reference numerals 7, 8, and 9 are switches for a user to set the state of the camera. In particular, the reference numeral 9 denotes a PLAY button. A reference numeral 13 denotes a display of the remaining number of recordable pictures. Object light which is incident into a prism 12 from a viewfinder front frame 3 is projected from a viewfinder eyepiece window 11. Reference numerals 10 and 14 denote an image pickup system and a connection terminal for connecting to an external computer or the like to transmit and receive

data, respectively.

The schematic structure of a signal processing system is now described.

Fig. 14 is a block diagram of the signal processing system. This camera is a single plate type digital color camera using a solid-state image pickup element 120 such as a CCD or a CMOS sensor. Image signals representing a dynamic image or a still image are obtained by driving the solid-state image pickup element 120 continuously or only once. Here, the solid-state image pickup element 120 is an image pickup device of the type which converts exposed light into electric signals with regard to the respective pixels, stores respective charges according to the light amount, and reads the respective charges.

It is to be noted that Fig. 14 only shows portions which are directly relevant to the present invention, and illustration and description of portions which are not directly relevant to the present invention are omitted.

As shown in Fig. 14, the image pickup apparatus has the image pickup system 10, an image processing system 20 as an image processing means, a recording and reproduction system 30, and a control system 40. Further, the image pickup system 10 includes an objective lens 100, a diaphragm 110, and the solid-state image pickup element 120. The image processing system 20 includes an A/D converter 500, an RGB image processing circuit 210, and a YC processing circuit 230. The recording and reproduction system 30 includes a recording processing circuit 300 and a reproduction processing circuit 310. The control system 40 includes therein a system control unit 400, an operation detection circuit 410, and a drive circuit 420 of the solid-state image pickup element.

The image pickup system 10 is an optical processing system for imaging light incident from an object through the diaphragm 110 and the objective lens 100, on an image pickup plane of the solid-state image pickup element. The light transmission factor of the objective lens 100 is adjusted to expose a subject image of 5 an appropriate light amount to the solid-state image pickup element 120. As described above, as the solid-state image pickup element 120, an image pickup device such as a CCD and a CMOS sensor is applied. By controlling the exposure time and the exposure intervals of the solid-state image pickup element 120, image signals representing continuous dynamic images or image signals representing a still 10 image by one exposure can be obtained.

Fig. 1 is a detailed view of the image pickup system 10. First, the diaphragm 110 has three circular openings 110a, 110b, and 110c as shown in Fig. 3. Object light which enters a light incidence plane 100e of the objective lens 100 from the openings are projected from three lens portions 100a, 100b, and 100c of the 15 objective lens 100 to form three object images on the image pickup plane of the solid-state image pickup element 120. The diaphragm 110, the light incidence plane 100e, and the image pickup plane of the solid-state image pickup element 120 are in parallel with one another. In this way, by making weak the power on the incidence side, making strong the power on the projection side, and providing a diaphragm on 20 the incidence side, the curvature of the image plane can be reduced. It is to be noted that, though the light incidence plane 100e of the objective lens 100 is a plane here, the light incidence plane 100e may be formed of three spherical surfaces or three rotation-symmetry nonspherical surfaces.

The three lens portions 100a, 100b, and 100c have circular spherical surface portions as shown in Fig. 5 showing the objective lens 100 viewed from the side where light is projected. An infrared radiation-cutting filter having a low transmission factor with regard to the wavelength range of equal to or greater than 670 nm is formed on the spherical surface portions while a light-shielding layer is formed on a plane portion 100d shown with hatching. More specifically, the objective optical system is formed with the objective lens 100 and the diaphragm 110, while the three lens portions 100a, 100b, and 100c are the imaging system.

In the present embodiment, the first image pickup region according to the present invention corresponds to an image pickup region 120a while the second image pickup region according to the present invention corresponds to an image pickup region 120b or 120c. The first imaging system corresponds to the lens portion 100a while the second imaging system corresponds to the lens portion 100b or 100c. Further, the first object image corresponds to an object image formed within an image circle 51a while the second object image corresponds to an object image formed within an image circle 51b or 51c. The first image signal corresponds to a G image signal while the second image signal corresponds to an R image signal or a B image signal.

Manufacturing is easy using glass molding if the objective lens 100 is made of glass, and using injection molding if the objection lens 100 is made of resin.

Fig. 2 is a front view of the solid-state image pickup element 120. The solid-state image pickup element 120 is provided with three image pickup regions 120a, 120b, and 120c corresponding to the three formed object images. Each of the

image pickup regions 120a, 12b, and 120c are sized to be 2.24 mm x 1.68 mm, with the arrangement of 800 x 600 pixels having the vertical and horizontal pitch of 2.8 μ m. The size of the image pickup regions combined is 2.24 mm x 5.04 mm. The diagonal size of each of the image pickup regions is 2.80 mm. In the figure, image 5 circles 51a, 51b, and 51c, within which an object image is formed, are circular, and the sizes of the circles are determined by the size of the openings of the diaphragm and the spherical surface portions on the projection side of the objective lens 100. The image circles 51a and 51b overlap each other and the image circles 51b and 51c overlap each other.

10 In Fig. 1, hatched portions 52a, 52b, and 52c sandwiched between the diaphragm 110 and the objective lens 100 are optical filters formed on the light incidence plane 100e of the objective lens 100. As shown in Fig. 4 showing the objective lens 100 viewed from the light incidence side, the optical filters 52a, 52b, and 52c are formed in regions which completely include the diaphragm openings 110a, 110b, and 110c, respectively.

15 The optical filter 52a has spectral transmission factor characteristics shown as G in Fig. 6 which mainly transmit green, the optical filter 52b has spectral transmission factor characteristics shown as R which mainly transmit red, and the optical filter 52c has spectral transmission factor characteristics shown as B which mainly transmit blue, and thus, these are primary color filters. As the product with the characteristics of the infrared radiation cutting filter formed on the lens portions 20 100a, 100b, and 100c, the object images formed in the image circles 51a, 51b, and 51c are of the green light component, the red light component, and the blue light

component, respectively.

On the other hand, optical filters 53a, 53b, and 53c are formed on the three image pickup regions 120a, 120b, and 120c, respectively, of the solid-state image pickup element 120. Their spectral transmission factor characteristics are equivalent to the ones shown in Fig. 6. More specifically, the image pickup regions 120a, 120b, and 120c are sensitive to green light (G), red light (R), and blue light (B), respectively.

Since the spectral distributions of the received light of the respective image pickup regions are given as the product of the spectral transmission factors of the pupils and the spectral transmission factors of the image pickup regions,

respectively, the combination of the pupil and the image pickup region is selected according to the wavelength range. More specifically, object light which goes through the diaphragm opening 110a is mainly photoelectrically converted in the image pickup region 120a, object light which goes through the diaphragm opening

110b is mainly photoelectrically converted in the image pickup region 120b, and object light which goes through the diaphragm opening 110c is mainly

photoelectrically converted in the image pickup region 120c. In other words, the image pickup regions 120a, 120b, and 120c output a G image, an R image, and a B image, respectively. In this way, by using multiple optical filters for the purpose of

color separation on the pupils of the image pickup optical system and on the image pickup element, the color purity can be enhanced. This is because, by using the same kind of optical filters twice, the buildup of the transmission factor characteristics becomes steeper and the red color (R) and the blue color (B) do not

overlap with each other. It is to be noted that the transmission factors of the optical filters 52a, 52b, and 52c, or of the optical filters 53a, 53b, and 53c, are preferably set so as to provide appropriate signal levels in the respective image pickup regions in the same accumulation time.

5 In the image processing system 20, a color image is formed based on the selective photoelectric conversion output obtained from the plurality of images by the plurality of image pickup regions of the solid-state image pickup element 120, respectively. Here, since the peak wavelength of the spectral luminous efficiency is 555 nm, the signal processing is carried out using a G image signal including this 10 wavelength, as the reference image signal.

When the pixel pitch of the solid-state image pickup element is fixed, compared with a system adopted generally by a digital color camera in which an RGB color filter is formed on the solid-state image pickup element with, for example, a 2 x 2 pixel block basis to provide wavelength selectability to each pixel, 15 and thus, an object image is separated into RGB images, the size of the object image is $1/\sqrt{3}$ times. Thus, the focal length of the objective lens is about $1/\sqrt{3}$ times, which is quite advantageous in making the camera thinner.

It is to be noted that, with regard to the spectral transmission factor characteristics of the optical filters 52a, 52b, and 52c, and of the optical filters 53a, 20 53b, and 53c, as shown in Fig. 6, R and G overlap each other, and G and B overlap each other, though R and B are almost separated from each other.

Therefore, even when the image circle 51b of the red light overlaps the image pickup region 120c for photoelectrically converting the blue light, and

conversely, even when the image circle 51c of the blue light overlaps the image pickup region 120b for photoelectrically converting the red light, these images do not become the output of the image pickup regions. However, at the portion where the image circle 51b of the red light overlaps the image pickup region 120a for photoelectrically converting the green light, and at the portion where the image circle 51a of the green light overlaps the image pickup region 120b for photoelectrically converting the red light, a small amount of an image of a different wavelength which should be blocked is superimposed. More specifically, since the selectivity of the object image is given by the product of the spectral transmission factor characteristics of the optical filter 52a and the spectral transmission factor characteristics of the optical filter 53b, and by the product of the spectral transmission factor characteristics of the optical filter 52b and the spectral transmission factor characteristics of the optical filter 53a, the cross talk of the R image signal and the G image signal does not become zero although it is small.

Therefore, the objective lens 100 is further provided with characteristics to lower the transmission factor of the wavelength range of the portion where R and G overlap each other. This can be carried out by using optical filtering technology implemented by a color purity correction filter.

The color purity correction filter is an optical filter formed of a base material made of a transparent synthetic resin or glass having a predetermined amount of rare-earth metal ions contained therein.

As the rare-earth metal ions, one or more selected among neodymium ions, praseodymium ions, erbium ions, holmium ions are used. However, it is preferable

that at least neodymium ions are used as indispensable ions. It is to be noted that trivalence ions are generally used as these ions. The content of the metal ions is selected in a range of normally 0.01 to 40 mass parts, preferably 0.04 to 30 mass parts relative to 100 mass parts of the base material of the objective lens 100.

5 As shown in Fig. 7, the color purity correction filter has characteristics to selectively absorb light in a predetermined wavelength range between the peak wavelengths of the color components of R, G, and B to decrease the amount of transmission thereof. This action almost eliminates cross talk due to the overlap of the image circle 51b of the red light and the image pickup region 120a for 10 photoelectrically converting the green light and the overlap of the image circle 51a of the green light and the image pickup region 120b for photoelectrically converting the red light.

Further, the objective lens 100 is also provided with photochromic characteristics which allow the lens to be darkened by light and to be reversibly achromatized when the irradiation of light is stopped. This is for suppressing the 15 amount of light reaching the solid-state image pickup element when the field is extremely bright, and thereby enlarging the recordable intensity range, since the accumulation time control range of the solid-state image pickup element 120 is limited.

20 An example of the photochromic glass that may be used in this invention is photochromic glass of phosphate glass made by Chance-Pilkington which has been put to practical use for spectacles (Product name: Reactolite Rapide).

Fig. 8 is a graph showing the spectral transmission factor characteristics of

a photochromic glass used as the objective lens 100. In Fig. 8, a solid line shows the characteristics after exposure to sunlight for 20 minutes while a broken line shows the characteristics with no exposure to sunlight. When the camera is carried about with the user outdoors under a blue sky or the like, light beams which enter the
5 objective lens 100 from the diaphragm 110 makes the objective lens 100 itself darkened to reduce by about $\frac{1}{2}$ the amount of light entering the solid-state image pickup element 120. As a result, the accumulation time can be made twice as long, which raises the control limitation on the high intensity side.

The screen size of each of the image pickup regions 120a, 120b, and 120c
10 is 2.24 mm x 1.68 mm as described above, since the pixel pitch is 2.8 μm and the number of the pixels are 800 x 600. The diagonal screen size of each of the image pickup regions is 2.80 mm. Generally, when the image pickup angle θ of a small-sized camera is about 70° in the diagonal direction, the camera is most convenient. When the image pickup angle is 70° , the focal length is 2.0 mm in this
15 case, since it is determined by the diagonal size of the screen.

When a person or the like is the subject of recording, considering that a person is about 170 cm tall and one person to three people are often recorded at a time, a virtual distance D(m) to the subject can be defined as in the following equation (1) as a function of the image pickup angle $\theta(^\circ)$:

20
$$D = 1.4 / \tan(\theta/2) \quad \dots(1)$$

Substituting 70° for θ of equation (1), $D = 2.0$ m is obtained. Here, if the image pickup system 10 is formed so as to optimally focus on the subject from a distance of 2 m, the letting out of the lens from the point at infinity is 0.002 mm.

Taking into consideration the allowable circle of confusion to be described later, there is practically no problem even if the image pickup system is a fixed focus image pickup optical system without a mechanism for letting the lens out.

A focal length f of a planoconvex lens put in the air can be represented as follows:

$$f = \{1 / (1-n)\} r \quad \dots(2)$$

wherein n is the index of refraction and r is the radius of the spherical surface.

Therefore, if the index of refraction n of the objective lens 100 is 1.5, for example, r for obtaining the focal length of 2.0 mm is 1.0 mm.

It is convenient to make equal the sizes of the red, green, and blue object images, since there is no need to make correction of the image magnification, and thus, the processing time is not elongated. Therefore, the lens portions 100a, 100b, and 100c are optimized for the peak wavelengths of 530 nm, 620 nm, and 450 nm of the light which goes through the RGB optical filters, respectively, to equalize the magnifications of the respective images. This can be paraxially accomplished by equalizing the distance from the positions of the principal points of the respective lens portions to the solid-state image pickup element.

In case of glass with an index of refraction of the d line (587.6 nm) $n_d = 1.5$ and an Abbe number $v_d = 60$, the indices of refraction at the wavelengths of 530 nm, 620 nm, and 450 nm are about 1.503, 1.499, and 1.509, respectively. If all the radii r of the spherical surfaces of the lens portions 100a, 100b, and 100c equal -1.0 mm, the focal lengths at the respective wavelengths are, by the equation (2), as follows:

the lens portion 100a having the representative wavelength of 530 nm :

1.988 mm,

the lens portion 100b having the representative wavelength of 620 nm :

2.004 mm, and

the lens portion 100c having the representative wavelength of 450 nm :

5 1.965 mm.

Suppose from the pixel pitch that the allowable circle of confusion is 3.0 μm , and further suppose that the f-number of the objective lens is F5.6, the depth of focus represented as the product of the two is 16.8 μm . It can be seen that the difference 0.039 mm between the focal length in case of 620 nm and the focal length in case of 450 nm already exceeds this. More specifically, though the paraxial image magnifications are the same, depending on the color of the subject, the subject may be out of focus. Since the spectral transmission factor of an object normally ranges over a wide wavelength range, it is quite rare that a sharp image in focus can be obtained.

15 Accordingly, the radii r of the spherical surfaces of the lens portions 100a, 100b, and 100c are optimized with regard to the respective representative wavelengths. More specifically, here, no achromatism for removing the chromatic aberration over the whole visible region is not carried out and designs for the wavelengths are applied to the respective lenses. First, the equation (2) is transformed to obtain the following equation (3):

$$r = (1-n) f \quad \dots(3)$$

Inserting $f = 2.0$ and inserting in sequence $n = 1.503$, $n = 1.499$, and $n = 1.509$ in the equation (3), the following respective radii are calculated:

- the lens portion 100a having the representative wavelength of 530 nm : r =
-1.006 mm,
- the lens portion 100b having the representative wavelength of 620 nm : r =
-0.998 mm, and
- 5 the lens portion 100c having the representative wavelength of 450 nm : r =
-1.018 mm.

In order to optimally balance the difference in the image magnifications at a high position of an image, the heights of the vertices of the lens portions 100a, 100b, and 100c are slightly adjusted to make both the sharpness and the image
10 magnification ideal. Further, non-spherical surfaces are used for the respective lens portions to satisfactorily correct the curvature of the image plane. Distortion of the image can be corrected in the signal processing to be carried out later.

In this way, when reference G image signals by the green object light including the wavelength of 555 nm which has the highest luminosity factor and
15 image signals by the red and blue object lights, respectively, are obtained, and different focal lengths are set (the lens portions 100a to 100c are set at different focal length with regard to light other than the spectral distributions having the above representative wavelengths) with regard to one wavelength (for example, green of the wavelength of 555 nm having the highest luminosity factor) and a substantially
20 equal focal length is set with regard to the representative wavelengths in the respective spectral distribution in the imaging system, then by compositing these image signals, a color image with satisfactory correction of the chromatic aberration can be obtained. Since each of the imaging systems is formed of one lens, there can

be also attained technological advantage of making the imaging system thinner. Further, though achromatism normally requires a combination of two lenses having different dispersions, the achromatism is carried out here by only one lens, and thus attaining an additional technological advantage of lowering the cost.

5 The objective lens 100 is required to have high contrast image dissection up to the spatial frequency range as high as the pixel pitch. The image pickup system 10 takes in three object images with regard to the three wavelength ranges, and thus, compared with an image pickup system provided with a mosaic optical filter such as of the Baiyer arrangement having the same number of pixels, as described in the 10 above, the focal length is about $1/\sqrt{3}$ times to attain the same image pickup angle. Therefore, it is necessary to achieve high contrast image dissection of the higher spatial frequency component. The optimization with regard to the respective wavelengths of the lens portions described in the above is a technology for suppressing the chromatic aberration for the purpose of achieving this.

15 Generally, there are two methods of improving the aberration characteristics of an image pickup optical system to make spurious resolution less liable to occur, and thereby alleviating problems. One method is to increase the degree of freedom in designing by, for example, increasing the number of lenses forming the system, by making the lenses nonspherical, using anomalous dispersion 20 glass, or by complexly using diffraction optical elements. The other method is to make narrower the imaging light beam.

 The former method, increasing the degree of freedom in designing, though the focal length is $1/\sqrt{3}$ times, tends to increase the complexity of the structure of the

objective optical system. This works against thinning of the image pickup apparatus, and thus, is inappropriate. On the other hand, the latter method, using a narrower light beam, conforms to a thin image pickup apparatus.

When an imaging light beam is made narrower, as shown by a solid line b in Fig. 10, the response function referred to as OTF presents a gradual monotone decrease in the low frequency component, and after that, becomes slightly negative, and then, becomes slightly positive. On the other hand, in case a broad light beam without narrowing is used, as shown by a broken line a in Fig. 10, the response function presents a steep decrease in the low frequency component, and after that, becomes temporarily negative, and then, becomes positive again.

The state where the OTF is negative indicates occurrence of spurious resolution. This corresponds to an actual state where reversal of negative/positive occurs, that is, a portion which should be white is black while a portion which should be black is white. It makes it clear that a natural image can be obtained by making narrower the imaging light beam.

However, when the imaging light beam is made extremely narrow, the contrast in a high frequency range is decreased due to diffraction of light. In this state, an image is formed of a bright spot at the center and diffraction stripes surrounding the bright spot. These are caused by, as known well, a relative increase in the intensity of the diffraction stripes due to peripheral waves generated on the periphery of the opening of the diaphragm.

The diffraction stripes can be decreased by adding to the objective lens a filter which is transparent at the center and becomes darker toward the periphery.

This method is referred to as apodization, which is described in detail on pages 172 to 174 of "Kogaku Gijutsu Handbook Zohoban (Handbook of Optical Technology, Enlarged Edition)" (1975, Asakura Shoten).

Fig. 9 is a graph showing the transmission factor distribution of
5 transmission factor distribution type filters provided on the light incidence plane
100e of the objective lens 100 so as to face the diaphragm openings 110a, 110b, and
110c. The transmission factor distribution type filters are denoted as 54a, 54b, and
10 54c in Fig. 1. The positions where the transmission factor is the highest correspond
to the centers of the diaphragm openings 110a, 110b, and 110c, while the positions
where the transmission factor is zero correspond to the periphery of the openings
110a, 110b, and 110c, respectively, of the diaphragm. In other words, the
transmission factor is distributed so as to be the highest at the centers of the
diaphragm openings and so as to monotonically decrease toward their periphery.

Such a transmission factor distribution type filter is formed by forming a
15 thin film of Inconel, Chromel, chromium, or the like, by vapor deposition or
sputtering on the light incidence side of the objective lens 100. The characteristics
shown in Fig. 9 can be obtained by making the thin film the thinnest at the center
and the thickest on the periphery. It is to be noted that, in forming such a thin film,
19 the position of a mask used in the vapor deposition or sputtering is continuously
controlled.

Though the transmission factor distribution type filters 54a, 54b, and 54c
are formed on the objective lens here, the structure may be such that they are formed
on a glass plate and are arranged on the light incidence side or the light projection

side of the objective lens 100.

Fig. 11 is a graph showing the intensity distribution in an image. In the figure, a broken line a shows a case where the transmission factor is constant over the whole diaphragm opening, while a solid line b shows a case where the transmission factor is decreased from the center of the diaphragm opening toward the periphery. Compared with the case of the characteristics shown by a, there is no bound on the periphery of the image in the characteristics shown by b, which clearly shows that the image formed is satisfactory. This provides a technological advantage of decreasing the diffraction stripes by decreasing peripheral light beams by means of apodization.

Next, the relationship between the objective lens and the image pickup regions is described. Since the image pickup system has three lens portions, the positions of the three object images relatively change according to the distance to the subject. As described above, each of the image pickup regions is sized to be 2.24 mm x 1.68 mm, and the image pickup regions are arranged adjacent to each other with their long sides being in contact with each other. Therefore, the center-to-center distance of adjoining image pickup regions is 1.68 mm. In the YC processing circuit 230 to be described later, signal processing is carried out on the assumption that the center of an object image is the center of the image pickup region. When an object image with the virtual object distance of 2 m is to be formed on the image pickup portion at the same intervals as that distance, as shown in Fig. 12, the interval between the lens portions 100a and 100b and between the lens portions 100b and 100c is set to be 1.6783 mm. In the figure, arrows 55a, 55b, and 55c denote imaging

systems having positive power by the three lens portions 100a, 100b, and 100c of the objective lens 100, respectively, rectangles 56a, 56b, and 56c denote the ranges of the image pickup regions 120a, 120b, and 120c, respectively, and L1, L2, and L3 are optical axes of the imaging systems 55a, 55b, and 55c, respectively. Since the light incidence surface of the objective lens 100 is a plane and the lens portions 100a, 100b, and 100c to be the light projection surface are spherical surfaces, perpendiculares from the respective centers of the spheres to the light incidence plane 100e are the optical axes.

Here, as shown in Fig. 13, images of an object at infinity are formed at the same intervals as that of the lens portions 100a, 100b, and 100c, and thus, the interval between the G object image and the R object image and the interval between the R object image and the B object image are 1.6783 mm, which is a little smaller than the center-to-center distance of the image pickup regions of 1.68 mm. The difference ΔY is 0.0017 mm, i.e., 1.7 μm . With the G object image which has the highest luminosity factor being the reference object image, when the B object image moves, the difference ΔY doubles to 3.4 μm . Since it is often the case that a short-range object such as a person is positioned in the middle of a picture to be picked up and that a long-range object is positioned on the periphery of the picture, and, since the aberration of the objective lens increases on the periphery of the picture to lower the quality of an image, it can be understood that there is practically no problem if the maximum image interval change is smaller than the pixel pitch multiplied by two. As described in the above, since the pixel pitch P of the solid-state image pickup element 120 is 2.8 μm , it follows that $\Delta Y < 2 \times P$, and thus,

the color misalignment in an image at infinity to this extent is allowable.

Further, the interval between the images varies also according to temperature change of the image pickup system 10. Since the imaging magnification of the image- pickup system 10 is extremely small, the image interval variation ΔZ can be expressed as the difference between the expansion of the objective lens and the expansion of the solid-state image pickup element in the following equation (4):

$$Z = 1.68 \times (\alpha L - \alpha S) \times \Delta T \quad \dots(4)$$

wherein αS is the coefficient of linear expansion of the solid-state image pickup element 120, αL is the coefficient of linear expansion of the objective lens 100, and ΔT is the temperature change.

Here, when $\alpha S = 0.26 \times 10^{-5}$, $\Delta T = 20(^{\circ}\text{C})$, and the objective lens 100 is formed of low-melting glass and $\alpha L = 1.2 \times 10^{-5}$, ΔZ is calculated at 0.00032 (mm). This is the variation in the interval between the G object image and the R object image, and the variation in the interval between the R object image and the B object image.

When the B object image is regarded as a variation with respect to the G object image which is the reference image signals, since the interval between the images is 1.68×2 , the image interval variation is $\Delta Z \times 2 = 0.00063$ (mm). When the temperature range where the camera is used is 0 to 40°C , the deviation ΔT from the reference temperature of 20°C is 20°C . Here, if $\Delta Z \times 2$ is smaller than $\frac{1}{2}$ of the pixel pitch, there is practically no problem. Generally, the coefficient of linear expansion αS of the solid-state image pickup element 120 is as small as about $0.26 \times$

10⁻⁵, it is necessary to select the coefficient of linear expansion αL of the objective lens 100 so as to satisfy the following expression (5):

$$2 \times A \times (\alpha L - 0.26 \times 10^{-5}) \times 20 < \frac{1}{2} P \quad \dots(5)$$

wherein A is either the interval between the G image and the R image, or the interval

5 between the R image and the B image, and P is the pixel pitch.

Since the coefficient αL ($= 1.2 \times 10^{-5}$) of linear expansion of the objective lens 100 used in the above satisfies the relationship expressed by the expression (5), it can be understood that the material of the lens 100 is suitable for the camera.

Further, apart from the fluctuation of the image interval due to the distance 10 to the object and due to temperature change, a method referred to as pixel shift is used where, by shifting relatively the image pickup regions 120a, 120b, and 120c of the solid-state image pickup element by $\frac{1}{2}$ pixel, the resolution is made higher with a small number of pixels. The amount of the shift of $\frac{1}{2}$ pixel is set with regard to the virtual object distance of 2 m.

15 As shown in Fig. 15, the image pickup region 120b for outputting the R image signals and the image pickup region 120c for outputting the B image signals are arranged so as to be shifted by $\frac{1}{2}$ pixel both in the horizontal direction and in the vertical direction with respect to the image pickup region 120a for outputting the G image signals.

20 This pixel shift may be accomplished by making the lens portions 100b and 100c of the objective lens 100 slightly offset with respect to the lens portion 100a, or may be accomplished by making the image pickup regions 120b and 120c of the solid-state image pickup element 120 slightly offset with respect to the image pickup

region 120a.

In an optical filter arrangement such as the Bayer arrangement, since, for example, a pixel provided with a red optical filter or a pixel provided with a blue optical filter is arranged between pixels provided with a green optical filter, an optical low-pass filter for suppressing aliasing is necessary. However, if images having different spectral distributions are taken in with regard to different image pickup regions, pixels provided with the respective optical filters can be densely arranged. As a result, the influence of the aliasing is small. Thus, a high definition image can be obtained without the need for the optical low-pass filter. This makes it possible to miniaturize the image pickup system and to substantially lower the cost.

Next, the signal processing is described.

As described in the above, an image pickup device having 1,800 pixels in its lengthwise direction and 800 pixels in its breadthwise direction, i.e., having 1,440,000 pixels in total is effectively applied to the solid-state image pickup element 120. Optical filters of the three primary colors, that is, red (R), green (G), and blue (B), are arranged on its front surface in predetermined regions.

As shown in Fig. 14, image signals read from the solid-state image pickup element 120 are supplied to the A/D converter 500 of the image processing system 20. The A/D converter 500 is, for example, a signal converting circuit for converting the signals into digital signals of, for example, ten bits according to the amplitude of the signal of each pixel and for outputting the converted signals. Then, the image signal processing is carried out in digital processing.

The image processing system 20 has a signal processing circuit for

obtaining image signals of a desired format from R, G, and B digital signals, and for converting R, G, and B color signals into YC signals expressed by a luminance signal Y and chrominance signals (R-Y) and (B-Y), or the like.

The RGB image processing circuit 210 is a signal processing circuit for 5 processing the pixel signals of the 1800 x 800 pixels received from the solid-state image pickup element 120 through the A/D converter 500, and has a white balance circuit, a gamma control circuit, and an interpolation circuit for making the resolution higher by interpolation.

The YC processing circuit 230 is a signal processing circuit for generating a 10 luminance signal Y and chrominance signals R-Y and B-Y. The YC processing circuit 230 is formed of a high luminance signal generating circuit for generating high luminance signal YH, a low luminance signal generating circuit for generating a low luminance signal YL, and a chrominance signal generating circuit for generating chrominance signals R-Y and B-Y. A luminance signal Y is formed by 15 compositing a high luminance signal YH and a low luminance signal YL.

The RGB image processing circuit 210 is now described in detail.

RGB signals outputted through the A/D converter 500 with regard to the R, 20 G, and B regions, respectively, are first subject to predetermined white balance adjustment in the white balance circuit in the RGB image processing circuit 210, and then are subject to predetermined gamma control in the gamma control circuit.

The interpolation circuit in the RGB image processing circuit 210 generates, by interpolation, image signals having the resolution which is four times the 600 x 800 pixels, converts the image signals from the solid-state image pickup

element 120 into signals having high definition image quality, and supplies them to the high luminance signal generating circuit, the low luminance signal generating circuit, and the chrominance signal generating circuit at the subsequent stage.

Since the sizes of the R, G, and B object images are already the same based on the setting of the objective lens 100, first, by a publicly known method, arithmetic processing for correcting optical aberration of the objective optical system is carried out with regard to the respective image signals. After that, the interpolation processing, the luminance signal processing, and the chrominance signal processing which are the same as those of an ordinary digital color camera are performed. The interpolation processing is as follows.

First, a G image signal which is a reference image signal from the image pickup region 120a is subject to interpolation according to the following equations (6) to (9):

$$G_{2i2j} = G_{ij} \quad \dots(6)$$

$$G_{2i(2j+1)} = G_{ij} \cdot \frac{1}{2} + G_{(j+1)j} \cdot \frac{1}{2} \quad \dots(7)$$

$$G_{(2i+1)2j} = G_{ij} \cdot \frac{1}{2} + G_{(i+1)j} \cdot \frac{1}{2} \quad \dots(8)$$

$$\begin{aligned} G_{(2i+1)(2j+1)} = & G_{ij} \cdot \frac{1}{4} + G_{(j+1)j} \cdot \frac{1}{4} + \\ & G_{(i+1)j} \cdot \frac{1}{4} + G_{(i+1)(j+1)} \cdot \frac{1}{4} \end{aligned} \quad \dots(9)$$

This is, 16 G elements are generated from each four G pixels, and thus the G image signals of 600 x 800 pixels from the image pickup region 120a are converted into 1200 x 1600 pixels.

Then, R image signals from the image pickup region 120b corresponding to the respective positions of the G image signals calculated using the above equations

(6) to (9) are subject to interpolation according to the following equations (10) to
13):

$$R_{2i2j} = R(i-1)(j-1) \cdot 1/4 + R(i-1)j \cdot 1/4 + \\ R(i-1)j \cdot 1/4 + Rij \cdot 1/4 \quad \dots(10)$$

5 $R_{2i(2j+1)} = R(i-1)j \cdot 1/2 + Rij \cdot 1/2 \quad \dots(11)$

$$R(2i+1)2j = R(i-1)j \cdot 1/2 + Rij \cdot 1/2 \quad \dots(12)$$

$$R(2i+1)(2j+1) = Rij \quad \dots(13)$$

Since, as described above, the image pickup region of the R object image
and the image pickup region of the B object image are arranged so as to be shifted by
10 $\frac{1}{2}$ pixel from the image pickup region of the G object image, the original output of
the ij address is applied to the $(2i+1)(2j+1)$ address as indicated by the equation (13).

Similarly to the R image signals, B image signals from the image pickup
region 120c corresponding to the respective positions of the G image signals
calculated using the above equations (6) to (9) are subject to interpolation according
15 to the following equations (14) to (17):

$$B_{2i2j} = B(i-1)(j-1) \cdot 1/4 + B(i-1)j \cdot 1/4 + \\ Bi(j-1) \cdot 1/4 + Bij \cdot 1/4 \quad \dots(14)$$

20 $B_{2i(2j+1)} = B(i-1)j \cdot 1/2 + Bij \cdot 1/2 \quad \dots(15)$

$$B(2i+1)2j = Bi(j-1) \cdot 1/2 + Bij \cdot 1/2 \quad \dots(16)$$

25 $B(2i+1)(2j+1) = Bij \quad \dots(17)$

By the above processing, the R, G, and B signals of 600 x 800 pixels from
the image pickup regions 120a, 120b, and 120c are converted into R, G, and B
signals of 1200 x 1600 pixels, respectively, having high definition image quality.

The high luminance signal generating circuit in the YC processing circuit
230 is a publicly known signal forming circuit for forming a high luminance signal
YH from a color signal having the highest spatial frequency component among color
component signals. The low luminance signal generating circuit is a publicly known
5 signal forming circuit for forming luminance signal YL of low frequency from a
signal containing all the color components of R, G, and B. The chrominance signal
generating circuit is a publicly known arithmetic circuit for calculating chrominance
signals R-Y and B-Y from high definition RGB signals.

The recording and reproduction system 30 is a processing system for
10 outputting image signals to the memory and outputting image signals to the liquid
crystal monitor 4, and includes a recording processing circuit 300 for writing and
reading image signals in and from the memory and a reproduction processing circuit
310 for reproducing image signals read from the memory as output to the monitor.
More specifically, the recording processing circuit 300 includes a compressing and
15 expanding circuit for compressing YC signals representing a still image or a
dynamic image according to a predetermined compression format and for expanding
the compressed data when it is read from the memory. The compressing and
expanding circuit includes a frame memory for signal processing and the like. YC
signals from the image processing system 20 are stored on a frame basis, the signals
20 are read on a plurality of blocks basis, and the signals are compression encoded. The
compression encoding is carried out by, for example, two-dimensional orthogonal
transformation, normalization, and encoding, according to the Huffman method on
the block basis.

The reproduction processing circuit 310 is a circuit for carrying out matrix conversion of the luminance signal Y and the chrominance signals R-Y and B-Y into, for example, RGB signals. Signals converted by the reproduction processing circuit 310 are outputted to the liquid crystal monitor 4. Thus, a visible image is displayed and reproduced.

On the other hand, the control system 40 includes control circuits for controlling, in response to external operation, the image pickup system 10, the image processing system 20, and the recording and reproduction system 30, respectively. It detects depression of the RELEASE button 6 to control driving of the solid-state image pickup element 120, operation of the RGB image processing circuit 210, compression processing of the recording processing circuit 300, and the like. More specifically, the control system 40 includes an operation detection circuit 410 for detecting the operation of the RELEASE button 6, a system control unit 400 for controlling the respective portions in response to the detection signal and generating and outputting timing signals when an image is picked up and the like, and a drive circuit 420 for the solid-state image pickup element 120, which, under control of the system control unit 400, generates drive signals for driving the solid-state image pickup element 120.

Next, operation of the image pickup apparatus according to the present embodiment is described with reference to Figs. 14 and 17A to 17C. First, when the main switch 5 is turned on, power source voltage is supplied to the respective portions and then they become operable. Then, it is determined whether an image signal can be recorded or not in the memory. Here, the number of recordable

pictures is displayed on the display area 13 for the remaining number of pictures in a liquid crystal monitor 4 according to the remaining capacity. An operator sees the display and, if a picture is recordable, directs the camera to the field and presses down the RELEASE button 6.

5 When the RELEASE button 6 is halfway pressed down, the exposure time is calculated. When all the preparatory processing for taking a picture completes, the camera is in a recordable state, and the operator is informed of this through the display. When the RELEASE button 6 is fully depressed, the operation detection circuit 410 transmits the detection signal to the system control unit 400. Here, the 10 exposure time calculated in advance is counted. When the predetermined exposure time elapses, a timing signal is supplied to the drive circuit 420. Then, the drive circuit 420 generates horizontal and vertical drive signals to sequentially read each of the exposed 1600 x 800 pixels in the horizontal direction and in the vertical direction.

15 The read signals of respective pixels are converted by the A/D converter 500 into digital signals of a predetermined number of bits to be sequentially supplied to the RGB image processing circuit 210 of the image processing system 20. The RGB image processing circuit 210 carries out interpolation to quadruple the pixel resolution after white balance adjustment and gamma control, and supplies the 20 signals to the YC processing circuit 230.

In the YC processing circuit 230, the high luminance signal generating circuit generates high luminance signal YH with regard to the respective RGB pixels, and similarly, the low luminance signal generating circuit generates low

luminance signal YL. The calculated high luminance signal YH is output to an adder through a low-pass filter. In the same way, the low luminance signal YL is, after subtraction of the high luminance signal YH, output to the adder through the low pass filter. By this, the difference YL-YH between a high luminance signal and a low luminance signal is added to obtain an luminance signal Y. Similarly, the chrominance signal generating circuit generates and outputs chrominance signals R-Y and B-Y. Components of the output chrominance signals R-Y and B-Y, which come through the low-pass filter, are supplied to the recording processing circuit 300.

Next, the recording processing circuit 300 receives the YC signals, compresses the respective luminance signal Y and chrominance signals R-Y and B-Y with a predetermined still image compression method, and records them sequentially in the memory.

When a still image or a dynamic image is reproduced from image signals stored in the memory, the PLAY button 9 is depressed. Then, the operation detection circuit 410 detects this operation to supply a detection signal to the system control unit 400, which causes the recording processing circuit 300 to be driven. The driven recording processing circuit 300 reads the recorded content from the memory to display images on the liquid crystal monitor 4. The operator selects the desired image by depresssing a SELECT button, or the like.

The embodiment described above achieves the following technological advantages.

(1) An image pickup apparatus, provided with an objective lens of simple

structure, can be realized having high image quality with satisfactory correction of chromatic aberration.

(2) By using only one objective lens, a quite thin image pickup apparatus can be realized, which makes it possible to make a digital color camera of card-like 5 thinness.

(3) A quite advantageous image pickup optical system can be realized from the viewpoint of the cost compared with an image pickup optical system which corrects color aberration by utilizing a combination of a plurality of lenses.

(4) By forming object images for each of the wavelength ranges, pixels provided with the same kind of optical filters can be densely arranged, and, an image pickup system can be materialized which does not require an optical low-pass filter 10 for removing aliasing.

The individual components shown in schematic or block form in the drawings are all well-known in the camera arts, and their specific construction and 15 operation are not critical to the operation or best mode for carrying out the invention.

While the present invention has been described with respect to what are presently considered to be the preferred embodiments, it is to be understood that the invention is not limited to the disclosed embodiments. To the contrary, the invention is intended to cover various modifications and equivalent arrangements 20 included within the spirit and scope of the appended claims. The scope of the following claims is to be accorded the broadest interpretation so as to encompass all such modifications and equivalent structures and functions.

For example, in the described embodiment, optical filters used for the color

separation are primary color filters of red, green, and blue. However, the present invention is also applicable to a case where these filters are replaced by complementary color filters of cyan, magenta, and yellow.

Further, in the above embodiments, an object image having the highest luminosity factor (green) is used as a reference to describe change in the intervals between the object image having the highest luminosity factor and object images having other luminosity factors (other colors), which is caused by change in the distance to the object. However, the present invention is also applicable to a case where an object image having the highest luminosity factor (green) is not used as the reference.

Also, in the present invention, the whole or part of the appended claims or of the structure of an embodiment may form one apparatus, may be combined with another apparatus, or may be a constituent of an apparatus.